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Effect of Glacial and Polar Ice on Space Geodetic Observations

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I) Crustal Deformation Caused by Changing Polar Ice

We looked at the problem of using crustal motion measurements to constrain on-going changes in polar (ie. Greenland and Antarctic) ice. This work is described in the enclosed papers: "Predictions of vertical uplift caused by changing polar ice volumes on a viscoelastic earth" by Wahr, Han, and Trupin (GRL, 22, 977-980, 1995), and "Predictions of crustal deformation caused by changing polar ice on a viscoelastic earth" by Wahr and Han (submitted to Surveys in Geophysics). The results are briefly summarized here.

Any mass placed on the earth's surface will load and deform the earth. If the mass is large enough, the deformation could be evident in geodetic observations of crustal positions or of surface gravity. This offers the opportunity of using those observations to learn about the mass anomaly.

Of all the possible surface loads, those caused by changes in continental and polar ice are probably best suited to be constrained using crustal deformation measurements. Ice loads are apt to change relatively slowly and to have well-defined spatial boundaries. Both these factors tend to reduce the possible ambiguities of the measurement interpretation.

To illustrate the possible size of the loading effect, the vertical subsidence of the crust in response to a broad-scale surface load (ie. several hundred kilometers, or more, in extent), is about 2-3% of the load's equivalent water thickness. Put in these terms, the ±80 mm/yr range for the possible rate of change in the average Greenland ice thickness (from the most recent IPCC report of Warrick, et al, 1995) corresponds to a range of crustal uplifts of around ±2 mm/yr. Changes in ice thickness are not likely to be uniform over the ice sheets, and so there will be locations where the crustal displacements are larger than the average. For example, J. Zwally (1995; personal communication) has estimated from a recent analysis of Seasat and Geosat altimeter data, that much of the southern third of the Greenland ice sheet may be thickening at a rate of about 100-150 mm/yr, which could cause crustal displacement rates on the order of 2-4 mm/yr at the ice sheet margins in this region. And results from dynamical models of the Antarctic ice sheet suggest uplift rates around the edge of that ice sheet could also be as large as several mm/yr in places.

To put these results in perspective, vertical displacements from present-day GPS measurements are probably accurate to about 7 mm for averaging times of a week. The results get better with longer averaging times, so that one year of continuous GPS observations could conceivably provide a linear trend accurate to $\approx$ 2 mm/yr. Absolute gravity observations are probably accurate at the 1 μgal level for a week of data, which corresponds to about 3 mm of vertical motion.

These numbers suggest that it could be possible to detect crustal displacements caused by changes in polar ice after only 2-3 years of continuous GPS or absolute gravity data. But there are possible interpretive problems. For example, changes in ice load are apt to occur on seasonal and interannual time scales in addition to the secular variations described above. These shorter-term variations could obscure the secular term, though they are also of interest in their own right. Seasonal variability can best be determined by continuously monitoring crustal displacements with a permanently-installed instrument. Interannual fluctuations can not be separated from secular trends without several years of high-quality data.

Tectonic motion, both co-seismic and a-seismic, can cause secular variability. Both Greenland and Antarctica are far enough removed from tectonically-active regions, that this is probably not a concern for measurements made at the margins of those ice sheets. But, it is a general issue that must be considered whenever crustal motion measurements are used to infer surface loading.

Another problem for determining secular variability is the visco-elastic response of the earth to past loading events. For example, the earth is still responding to the Late Pleistocene deglaciation of

Northern Canada, Scandinavia, and Antarctica, with rates of vertical motion that may be as large as 10 mm/yr near the centers of those ancient ice sheets, and several mm/yr along the margins of Greenland and Antarctica. In addition, any rate of change of Greenland or Antarctic ice that has persisted over the past several hundred years or longer (periods typical of the earth's visco-elastic decay times), will likely have generated a visco-elastic response that is still affecting crustal motion today.

Since the visco-elastic effects on crustal motion measurements can easily be as large as or larger than the effects of present-day changes in polar ice, the visco-elastic effects must somehow be removed from the data. Any attempt to model those effects requires assumptions about the earth's viscosity profile and about the time history of the Greenland and Antarctic ice sheets over the last several centuries to millenia. This would cause such a model to be highly uncertain. We have found, however, that it is possible to remove the visco-elastic effects by simultaneously measuring the crustal uplift and surface gravity, and forming an appropriate linear combination of the results.

Specifically, let u and δg be the observed secular changes in vertical displacement and gravitational acceleration, respectively. Construct the secular change in the free air gravity anomaly:

$$\delta g_{fa} = \delta g - 2\frac{g}{a}u$$

where a is the radius of the earth and g is the total, unperturbed gravitational acceleration at the earth's surface. Then, we have found that the quantity

$$\Delta = u - A\,\delta g_{fa}$$

where $A = 6.5$ mm/μgals is approximately independent of the earth's viscoelastic response to past loading. Thus, results for Δ can be directly interpreted in terms of present-day changes in ice. Theoretical results in support of this conclusion can be seen in Figure 3 from the enclosed paper by Wahr, et al (1995).

II) Polar motion and Gravity From Mass Balance in Greenland and Antarctica

Existing models of ice thickness in Greenland and Antarctica were used to predict the elastic and visco-elastic part of vertical deformation and gravity. Satellite solutions to the low degree zonal coefficients of the Earth's gravity field have become reliable enough to be used to constrain the mass balance of polar ice, once they have been corrected for the effects of small glaciers, impoundments, post glacial rebound, and the non-steric rise in the oceans. This budgetary approach does not uniquely solve for the distribution of surface mass needed to produce the rotation and gravity changes for two reasons: inverse problem of the geopotential not only has no unique solution, and the many choices of lower mantle viscosity profile, time history of the loading, and spatial variation of ice thickness make the problem a severely under determined one. That is, an infinite number of combinations of mass distributions and loading histories can account for observations. As satellite solutions become more reliable, the approach is useful in the following way: Since Greenland is far enough away from the polar axis, spatial detail of the ice changes within Greenland have a smaller effect on both polar motion excitation and the low order zonal harmonic coefficients of the Earth's gravity than does the overall sea level contribution from Greenland or ice thickness changes in Antarctica. Thus a simple model for Greenland, such as a uniform discharge (calving of ice bergs around the periphery of the ice sheet) and a standard Benson line (division between net accumulation and ablation near the coast) can be assumed to find the shift the center of mass of the Antarctic ice sheet. This gives information as to whether coastal or interior regions of that ice sheet are thickening or thinning.

The results, presented in the attached paper, "Gravity and rotation changes from mass balance of polar ice" by Trupin and Panfili, submitted to Surveys of Geophysics, assume the runoff from Greenland was uniform (hence the thickness change was similar in profile to the surface mass balance) and that the Antarctic thickness change resembled the shape of the surface accumulation contours (but could be of different magnitude and sign). The contributions to the time rates of change even numbered low degree gravity coefficients have the opposite slope from the odd numbered coefficients for Antarctica but not for Greenland. The sea level contributions from the ice sheets must therefore not be too large, or the net gravity contribution would be larger than the observations, even if the sea level contribution from one ice sheet offset that of the other. The results for Antarctica show that the coastal regions are thickening and the interior regions experience ablation, but the sea level contributions from that ice sheet range from -0.025 to 0.5 mm/yr. Greenland sea level rise ranges from -0.2 to 0.26 mm/yr. Though the models of thickness change are just two of an infinite number of possible solutions, they are based on conservative assumptions in that the magnitude of the thickness change never exceeds the magnitude of the surface accumulation, and that the visco-elastic effects of the response of the loading for recent time histories, as well as prehistoric loading has been incorporated into the model in a consistent way. The authors are currently completing work on a similar study, entitled "An iterative forward solution to ice sheet thickness change from satellite solutions to gravity" that uses the same budgetary approach with gravity, but does not constrain the ice thickness to follow the surface accumulation in either shape or magnitude. The results will be submitted to Geopysical Research letters this spring. The apparent processes predicted by the models are common to a large family of solutions and are: For Antarctica, it appears that rising sea levels have undermined some of the grounded ice in the immediate periphery of the ice sheet, but that either heavy snowfall or plastic deformation of the ice dome have caused thickening of the ice in a peripheral ring just inside the continental boundary. Further into the interior, the models predict a net thinning of the ice sheet. The center of the Antarctic ice sheet is so close to the Earth's rotation axis that mass balance changes are not large enough to see in the solutions to the low degree coefficients. This highlights even more, the importance of ground based methods of discerning thickness change such as those as described above in Wahr, Han and Trupin, [1995].

We note that even though there is a very high quality time series in polar position, there are two poorly modeled contributions to polar motion that render these data relatively less useful in a budgetary constraint for ice mass balance. First, the effects of mantle convection and tectonic motion on polar motion is large and uncertain, see Spada et al, [1993], and second, the predicted polar motion contribution from post glacial rebound is very large, and varies rapidly with choice of lower mantle viscosity for low values of lower mantle viscosity. For a lower mantle viscosity that is very nearly that of the upper mantle, there is a very large predicted shift of polar position toward a point between Greenland and Scandinavia. This predicted polar drift is larger than the observed drift in the same general direction. For larger differences between upper and lower mantle viscosity, the effect on polar drift becomes smaller. For certain values of lower mantle viscosity in the range of $5.\times10^{21}$ to $50.\times10^{21}$ Pa-s, the large and negative y-component of the observed polar motion is almost entirely accounted for by post glacial rebound. [see Han and Wahr, 1993 and Wahr et al., 1992]. Thus we have used only the low degree coefficients to select for the mass balance profiles in best agreement with observation, but calculated the polar motion effects as a basis for future comparison.

III) Western North America and its relation to the Global water Budget

The current assumption, that most of the current rise in global sea level is due to the melting of small ice systems and thermal expansion, and that polar ice sheets are in equilibrium and to contribute little to present day sea level rise results in a "missing" component of sea level rise ranging from 0.4 to 1.0 mm/yr. The purpose of the North America study, see the attached paper, "Vertical motion and ice thickness variation in western North America" by Trupin and Easson, (accepted by Geophysical Research Letters, October, 1995, was to try to answer the question of whether prior estimates of glacial melt were too low, see Meier [1984] or Trupin, Meier, and Wahr [1990]. Could it be that the "missing water" in the oceans may not exist at all? For this region the visco-elastic effects are once again, large and measurable with current GPS capabilities, but are also seen in nearby tide gauges. To understand this region, an artificial data set had to be constructed for the ice covered area from sparse glacier mass balance data, and from mass balance versus altitude for 24 glaciers in the region. The equilibrium line elevations and the location of the ice covered area were read off maps and the inferred mass balance for the entire ice covered area was used to calculate the radial deformation. The effects of late Pleistocene de-glaciation and a simple model of the Little Ice Age were added to the present day crustal motion and the net vertical motion was compared with sea level records in nearby stations along the inside passage of Alaska. The signal of the retreating ice is clearly seen in the sea level records despite the large tectonic component, and the sea level contribution from just this region is larger than some earlier estimates of global wastage. If other regions that lie close to sea level have been underestimated, then the most of the non-steric portion of the sea level rise can be accounted for with mountain glacier melt. The two studies considered here are part of a larger picture of the global water budget, and the effects of ice thickness change are seen in gravity, rotation, and crustal motion.

IV) Student Participation and Educational Objectives

During the summers of 1993-1995, Five students, Raphael Panfili and Chris Hall, Damien Easson, Michael Niemat, and Michael Walsh at Vassar College, and two students are Grand Valley State University (Jonathan Levine and Chris Vroman) have participated in the research. They helped implement a graphics language (GMT) and write code in Fortran and IDL that calculates gravity and polar motion from the results of ice models. The Vassar students worked under the auspices of the Undergraduate Research Summer Institute (URSI) program.

A principal educational objective of this project was to provide students the means to work with geophysical data in a modern computing environment. Nasa has provided computing with a NeXT and Sun workstation and peripherals. A. Trupin intends to join Vassar's Undergraduate Summer Research Institute for the summer of 1996 so that a Vassar student may participate for 10 weeks during that season. We thank NASA for providing valuable support to the Physics and Astronomy department and hope that our work has been of value to the ongoing efforts in the Mission to Planet Earth and Geodynamics research programs.

References

Han, D. and J. Wahr, A new analysis of post-glacial rebound for a spherical Earth, *Geophys. J. Int.*, submitted, 1993.

Meier, M.F., Contribution of small glaciers to global sea level, *Science, 226,* 1418-1421, 1984

Spada, G., Y. Ricard, and R. Sabadini, Excitation of true polar wander by subduction, *Nature 360,* 453-454, 1992.

Trupin, A., M. Meier, and J. Wahr, Effect of Melting glaciers on the Earth's rotation and gravitational field: 1965-1984, *Geophys. J. Int., 108,* 1-15, 1992

Wahr, J., D. Han, A. Trupin and V. Lindqvist, Secular changes in gravity and rotation: Evidence of post glacial rebound or changes in polar ice?, *Advances in Space Research, 13,* (11)257-(11)269.

Wahr, J., D. Han, A. Trupin, Predictions of vertical uplift caused by changing polar ice volume on a viscoelastic Earth, *Geophys. Res. Lett, Vol 22, No. 8* 977-980, 1995

Warrick, H., H. Oerlemans, P. Woodworth, M. Meier, and C. Le Provost, 1995. Sea level change. in *The IPCC Second Scientific Assessment of Climate Change*, J. Houghton and L.G. Meira Filho, Cambridge Univ. Press, Cambridge.

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Trupin, A. and R. Panfili, Gravity and rotation changes from mass balance of polar ice, submitted to *Surveys in Geophysics*.

Trupin, A., D. Easson, and DaZhong Han, Vertical motion and ice thickness variations in western North America, *Geophysical research Letters*, (in press).

Wahr, J., D. Han, A. Trupin and V. Lindqvist, 1993. Secular changes in gravity and rotation: Evidence of post glacial rebound or changes in polar ice?, *Advances in Space Research, 13*, (11)257-(11)269.

Wahr, John M., Han Dazhong, and Andrew Trupin, 1995. Predictions of vertical uplift caused by changing polar ice volumes on a visco-elastic Earth, *Geophys. R. Lett., 22*, 977-980.

Wahr, John M. and Han Dazhong, Predictions of crustal deformation Caused by Changing Polar Ice on a Visco-Elastic Earth, submitted to *Surveys in Geophysics*.